Study of X-ray Kirkpatrick-Baez imaging with single layer

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The X-ray Kirkpatrick-Baez (KB) imaging experiment with single layer is implemented. Based on the astigmatism aberration and residual geometric aberration of a single mirror, a KB system with $16^{\times}$ mean magnification and approximately 0.45°grazing incidence angle is designed. The mirrors are deposited with an Ir layer of 20-nm thickness. Au grids backlit by X-ray tube of 8 keV are imaged via the KB system on scintillator charge-coupled device (CCD). In the ±80 μm field, resolutions of less than 5 μm are measured. The result is in good agreement with the simulated imaging.

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Kirkpatrick-Baez (KB) optics is a typical grazing incidence reflective imager at kiloelectronvolt (KeV) band of energy. For its higher spatial resolution (~5 μm) and collecting radiation efficiency than traditional X-ray pinhole camera, KB microscope is of critical importance for inertial confinement fusion (ICF)[1,2]. Especially after mid-1990s, many diagnostics using KB microscope were developed rapidly, such as the state equation measurement in Nova, the hydrodynamic stability of directly driven planar foils in Omega, and so on[3,4]. The used optical elements were single metal layer and multilayer. Single metal layer KB has higher reflectivity than multilayer KB, but the latter could go beyond the limit of critical angle and resolve spectrum[5,6]. By now, only one-dimensional imaging with 100-μm spatial resolution was implemented in China[7]. The essential reasons were the accuracy of grazing incidence angle and the detection efficiency. In this letter, we report the design and experiment of X-ray KB imaging with a single Ir layer, which realizes the spatial resolution of ~5 μm in the ±80 μm field.

The KB imager works based on the total external reflection of X-ray. It consists of two perpendicular concave spherical mirrors in tandem (as shown in Fig. 1). Rays from the object point are reflected by the first mirror (tangential mirror here) and form a tangential line while not a point. Similarly, rays via the second mirror (sagittal mirror here) form a sagittal line. Thus the perpendicular structure plays a role to overcome the strong astigmatism.

The imaging properties of each direction are described by the Coddington equations[8]. For tangential direction,

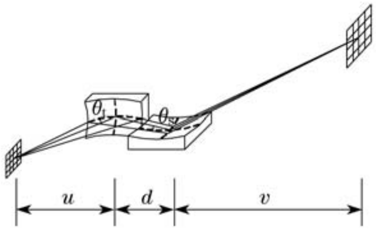

Fig. 1. Schematic diagram of KB optics.

$$\frac{1}{u}+\frac{1}{v+d}=\frac{1}{f_{\mathrm{t}}}=\frac{2}{R_{\mathrm{t}}\sin\theta_{\mathrm{t}}}, \quad (1)$$

and for sagittal direction,

$$\frac{1}{u+d}+\frac{1}{v}=\frac{1}{f_{\mathrm{s}}}=\frac{2}{R_{\mathrm{s}}\sin\theta_{\mathrm{s}}}, \quad (2)$$

where subscripts "t" and "s" refer to the tangential direction and sagittal direction, respectively, θ is the grazing incidence angle for the principal ray, u is the object distance, v is the image distance, d is the axial distance between the centers of mirrors, f is the focal length, and R is the curvature radius of mirror. With certain grazing incidence angles of θ_{t} and θ_{s}, the tangential focal line and sagittal focal line can be set in the same plane, which means the astigmatism is essentially eliminated.

In addition, the resolution is also limited by residual aberrations of single mirror. We have deduced the equations of geometric aberration in previous report[9]. The geometric aberration Y is given by

$$Y/M=\frac{3r^2}{2R}+\frac{2r}{R\sin\theta}q, \quad (3)$$

where r is the radius of mirror aperture, and q is the off-axis distance in object plane. Equation (2) is expressed clearly for Y/M due to that this quantity can be better measured for the resolution resulting from the geometric aberration than Y alone. Geometric aberration consists of on-axis spherical aberration of $\frac{3r^2}{2R}$ and off-axis aberration of $\frac{2r}{R\sin\theta}q$. Obviously, mirror aperture and field of view are essential factors related to the geometric aberration. A small mirror aperture will improve geometric aberrations, especially spherical aberration. But the flux will decrease greatly, which makes the detection very difficult. In addition, small mirror will make diffraction serious and decrease the resolution of central field. So the size of mirror aperture should be decided by the resolution requirement and actual flux together. Typically, the value is in the range of 4 − 10 mm[10,11]. Another relevant factor q is in proportion to the off-axis geometric aberration. So the resolution will decrease sharply with the increase of field. The field with 5-μm resolution is approximately ±100 μm, which is suited as the size of compressed core in ICF[12].

It must be noted that the image quality is also influenced by small-scale imperfections of mirrors. The primary imperfection is figure error, which makes the grazing incidence angle irregularly changed and the resolution decreases as a result. Surface roughness is another important imperfection. It causes the serious scattering and decreases the flux primarily. Generally, the surface error should be superior to the figure of $\lambda/20$ and roughness of 0.5 nm[13].

Based on the aberration analysis and actual requirements, the parameters are designed as follows: working energy $E = 8$ keV, curvature radius $R_{\rm t} = R_{\rm s}=$ 20 000 mm, object distance $u = 79.3$ mm, mean magnification $M = 16^{\times}$ ($M_{\rm t} = 16.1$, $M_{\rm s} = 14.2$), mirror aperture $d = 10$ mm, grazing incidence angles $\theta_t = 0.428°$ and $\theta_s = 0.478°$. The solid angle subtended by each reflecting pair as seen from the source is $\sim 9\times10^{-7}$ sr for this case. The fabrication errors are figure of $\lambda/10$ and roughness of 1 nm.

The substrate made of K9 glass was coated with 10-nm Cr initially and then an Ir layer was deposited onto the surface with a thickness of 20 nm. Reflectivity of the Ir mirror at 8-keV energy is shown as Fig. 2 from a calculation[14]. The reflectivity decreases sharply near 0.55°. At the working angles of 0.428° and 0.478°, the reflectivity is approximately 80%.

In order to ensure the perpendicularity of tangential mirror and sagittal mirror, they were adjusted using internal focusing telescope and penta prism. Then the two mirrors were assembled to be a whole on an object lens table. The X-ray source was homemade Cu target tube. The working voltage and current were 37 kV and 20 mA, respectively. The exposure time was 20 min. Au grids of 1500 lines/inch were backlit with X-rays. The separation of the grid in the mesh was 15.8 μm with the grid width of 6.03 μm and thickness of 12 μm, which were measured by scanning electron microscope (SEM). The image was recorded by a scintillator X-ray charge-coupled device (CCD) imager of 1 392×1 040 pixels and 6.45× 6.45 (μm) pixel-size (Photonic Science, XDI-50).

Alignment of the grazing incidence angle is an essential step in this experiment. It is a good idea to adjust the grazing incidence angle by directly imaging with KB at visible wavelength. However, the extreme small numerical aperture caused by grazing incidence makes it impossible. In this experiment, the numerical aperture is only 5×10^{-4}, the corresponding diffraction limit at

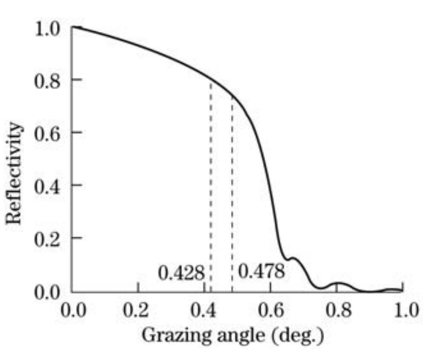

Fig. 2. Reflectivity of Ir layer of 20-nm thickness at 8 keV.

visible wavelength is up to 500 μm, which greatly exceeds the tolerance of grazing incidence angle. For X-ray of 8 keV ($\lambda = 0.154$ nm), the diffraction limit is only 0.18 μm and it can be ignored in alignment process. In experiment, we moved the mirrors to the center of X-ray beam firstly. Then the angle of mirrors was finely adjusted till the reflected focal line appeared. By measuring the distance between projective spots and one-dimensional reflected focal line, the grazing incidence angle was ensured.

The imaging results are shown in Fig. 3(a). The grids are distinct in the central field and gradually blur out with the increase of field. There are twelve distinct periods, corresponding to the size of 200 μm in the object plane. The ununiformity of brightness is due to the X-ray source, which has been tested by direct projection. Each grid image is not foursquare as the original shape. This change is caused by the difference of magnifications in tangential direction and sagittal direction.

Figure 3(b) shows the intensity distribution along

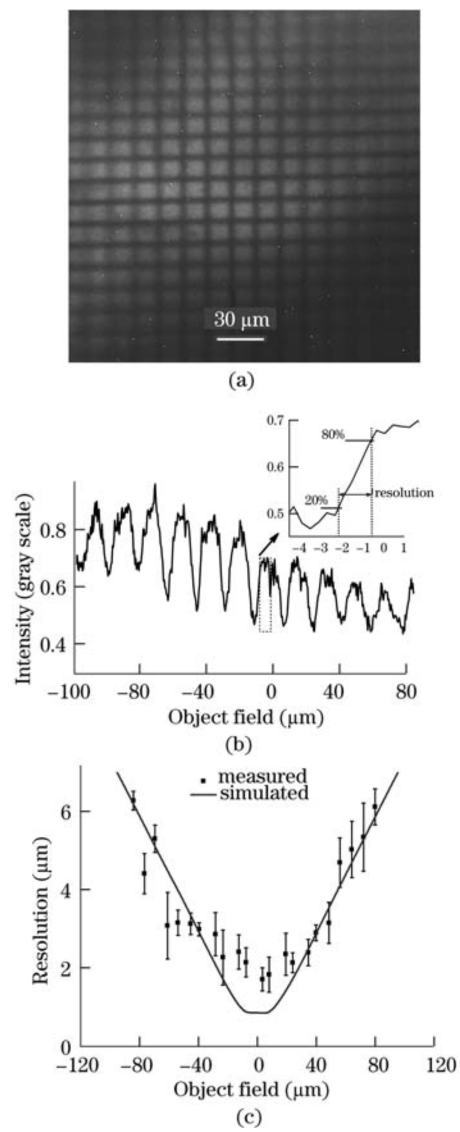

Fig. 3. Experimental results of imaging with KB optics. (a) Image of the backlit Au grids taken with a Cu X-ray tube; (b) intensity distribution along the horizontal direction; (c) comparison of measured resolution and simulated resolution.

the horizontal direction of Fig. 3(a). The values were computed intensity in normalized gray scale versus position in pixel (6.45 μm/pixel). The irregular change of intensity peak is due to the ununiformity of X-ray source. By the period of intensity along the horizontal direction, the actual magnification in the tangential direction could be calculated. The value is $(315/8 \times 6.45)/15.8=16.1$. In the same way, the magnification in the sagittal direction was calculated to be 14.1. Obviously, they coincide with the designed parameters perfectly.

The resolution function was measured from Fig. 3(b), which corresponded to the distance of 20% to 80% of the minimum intensity to the maximum intensity. Actual measurement results of spatial resolution (data points) are shown in Fig. 3(c). The error bar was obtained through five times measurement. By this resolution evaluating method, the resolution is measured approximately 2 μm in the central field, and less than 5 μm in the field of ± 80 μm. The solid line in Fig. 3(c) is the simulated resolution by ray tracing in ZEMAX. The measured resolution is in good agreement with the simulated resolution except for the on-axis case where it is likely that the small-scale imperfections of figure error and roughness are the most important.

In this letter, X-ray KB imaging with an Ir layer was investigated. Spatial resolution of approximately 5 μm was realized in the ± 80 μm field, which is close to the performance of KB microscope used in foreign laser facilities. For soft X-ray imaging for ICF, the grazing incidence angle could be larger. It will make the resolution better in identical field. In addition, multilayer technology, by which the grazing incidence angle can be expanded out of the critical angle, can improve the performance too.

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References

1. F. J. Marshall and Q. Su, Rev. Sci. Instrum. **66,** 725 (1995).
2. R. Rosch, J. Y. Boutin, J. P. le Breton, D. Gontier, J. P. Jadaud, C. Reverdin, G. Soullié, G. Lidove, and R. Maroni, Rev. Sci. Instrum. **78,** 033704 (2007).
3. O. V. Gotchev, P. A. Jaanimagi, J. P. Knauer, F. J. Marshall, D. D. Meyerhofer, N. L. Bassett, and J. B. Oliver, Rev. Sci. Instrum. **74,** 2178 (2003).
4. F. J. Marshall, M. M. Allen, J. P. Knauer, J. A. Oertel, and T. Archuleta, Phys. Plasmas **5,** 1118 (1998).
5. R. Chen, F. Wang, and Z. Wang, Chin. Opt. Lett. **6,** 310 (2008).
6. X. Cheng, Z. Wang, Z. Zhang, F. Wang, H. Wang, and L. Chen, Acta Opt. Sin. (in Chinese) **26,** 787 (2006).
7. C. Gu, Z. Wang, B. Mu, F. Wang, Z. Zhang, S. Qin, and L. Chen, Acta Photon. Sin. (in Chinese) **35,** 881 (2006).
8. P. Kirkpatrick and A. V. Baez, J. Opt. Soc. Am. **38,** 766 (1948).
9. B. Mu, S. Yi, S. Huang, and Z. Wang, High Power Laser and Particle Beams (in Chinese) **20,** 409 (2008).
10. O. V. Gotchev, L. J. Hayes, P. A. Jaanimagi, J. P. Knauer, F. J. Marshall, and D. D. Meyerhofer, Rev. Sci. Instrum. **74,** 5065 (2003).
11. G. R. Bennett, Appl. Opt. **40,** 4570 (2001).
12. F. J. Marshall and G. R. Bennett, Rev. Sci. Instrum. **70,** 617 (1999).
13. R. Kodama, N. Ikeda, Y. Kato, Y. Katori, T. Iwai, and K. Takeshi, Proc. SPIE **2523,** 165 (1995).
14. E. Spiller, *Soft X-Ray Optics* (SPIE, Washington, 1994) pp.23−31.